Investigation of Pore Fluid Pressure Variations from Crustal Deformation and Regional Gravity Flow: New Madrid Seismic Zone

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PIs: Lorraine W. Wolf and Ming-Kuo Lee
Auburn University

Department of Geology and Geography
210 Petrie Hall
Auburn University
Auburn, AL 36849
Ph.: 334.844.4878
FAX: 334.844.4486
wolflor@auburn.edu
www.auburn.edu/~wolflor

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Investigations undertaken.

This study is aimed at investigating the interrelationships of excess pore fluid pressures, seismicity, fault stability, and seismically induced liquefaction in the Mississippi Embayment. For model development and assessment, the proposed project will explore the development of anomalous fluid pressures resulting from regional gravity flow and seismic faulting in the New Madrid seismic zone (NMSZ) of the central United States. A documented history of widespread soil liquefaction, existing overpressures in the Mississippi Embayment, and the potential for large earthquakes makes this region an excellent candidate for study. In this project, we are initiating two aspects of hydrologic research related to seismic hazard: (1) a quantitative analysis of overpressure development in basin strata resulting from gravity flow and crustal deformation, and (2) a quantitative analysis of factors involved in overpressure development in near-surface sediments using simplified geologic models. The first aspect of the research involves the development of a quasi-coupled strain-fluid pressure model to track pore pressure changes initiated by large displacements along major faults, given simple models that approximate the geology to first order. The second aspect involves analyzing water levels in artesian wells and modeling the origin and distribution of excess pore pressure based on hydrostratigraphic relationships. The hydrogeologic data will be integrated with realistic groundwater flow models and with a growing body of geotechnical data to explore the interrelationship of near-surface hydrologic conditions with liquefaction susceptibility. The research will shed light on how the propagation of overpressures might affect deep fault stability and potential for near-surface earthquake-induced hazards. The specific objectives of the research are (1) to develop models to predict fluid pressure changes due to elastic strain generated by slip on major faults in the NMSZ; (2) to quantify the transient nature of pore pressure development and propagation using simple geologic models that consider thickness and permeability of confining layers; and (3) to test model predictions of fluid pressure variations against the present-day distribution of documented overpressures, geophysical anomalies, seismicity, and liquefaction deposits in the NMSZ.

The work pursued in this study is an expansion of a basin hydrology modeling project that has largely been completed (Browning, 2003; Wolf *et al.*, 2003; Wolf *et al.*, 2005). The ongoing project builds on previous work by integrating two numerical codes: 3D-DEF (Gomberg, 1993; Gomberg and Ellis, 1993, 1994) and 3PFLOW (Lee and Wolf, 1998).

Poroelasticity model development.

Our ultimate objective is to develop a 3-D fully coupled crustal deformation and time-dependent fluid flow model for the upper crust of the NMSZ. As a first step in this process, this study is aimed at developing a quasi-coupled 3-D strain-fluid pressure model. *Biot* [1941], *Wang* [2000], and *Showalter* [2000] summarized the physical and mathematical models for poroelastic problems. A set of partial differential equations can be used to solve for four basic variables: stress (σ), strain (ε), pore pressure (P), and increment of fluid content (ξ) in deformed porous media. First, the force equilibrium equations can be written as

$$\frac{\partial \sigma_{ji}}{\partial x_j} = -F_i \tag{1}$$

where σ_{ji} is the total stress in the *j*-direction acting on the surface with normal in the *i*-direction and F_i is a body force per unit bulk volume. The stress σ is related to strain and poroelastic moduli by

$$\sigma_{ij} = 2G\varepsilon_{ij} + 2G\frac{v}{1-2v}\varepsilon_{kk}\delta_{ij} - \alpha P\delta_{ij} \tag{2}$$

where G is shear modulus, v is drained Poisson's ratio, α is Biot-Willis coefficient, and δ_{ij} is the Kronecker delta. The strain components in equation (2) can be evaluated in terms of displacement derivatives

$$\varepsilon = \frac{1}{2}\left(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T\right) \quad . \tag{3}$$

Substituting equation (2) into (1) and replacing strain terms ε by displacements $\boldsymbol{u}$, the general force equilibrium equation (1) can be expressed as

$$-G\nabla^2\boldsymbol{u} - \frac{G}{1-2v}\nabla(\nabla\cdot\boldsymbol{u}) + \alpha\nabla P = \boldsymbol{F} \quad . \tag{4}$$

The governing mechanical equilibrium and fluid flow equations used here contain the displacement and fluid pressure as the primary variables.

For the flow continuity model, the propagation of induced excess pore pressure can be predicted by the general diffusion model,

$$S\frac{\partial P}{\partial t} - \nabla\cdot\left(\frac{k}{\mu}\nabla P\right) = Q \tag{5}$$

where S is the specific storage of rock, k is permeability, μ is viscosity, and Q is a fluid source term, as induced by seismic faulting. In heterogeneous media hydrologic properties k and μ are allowed to have spatial dependence. According to equation (5), the net pressure change depends on the magnitude of fluid source term Q and the permeability (k) and storage capacity (S) of the rocks between the faulting zone and a site of interest. The increment of fluid volume (ξ) released per unit bulk volume can be evaluated by

$$\xi = S\,P \quad . \tag{6}$$

Equation (5) can thus be re-written as in term of ξ

$$\frac{\partial \xi}{\partial t} - \nabla \cdot (\frac{k}{\mu} \nabla P) = Q \qquad . \tag{7}$$

Furthermore, the increment of fluid volume ξ is related to stress and pore pressure as

$$\xi = \frac{1}{H}\sigma_{kk} + \frac{1}{R}P = \frac{\alpha}{K}\sigma_{kk} + \frac{\alpha}{KB}P\,, \tag{8}$$

where *1/H* is the poroelastic expansion coefficient, *1/R* is the unconstrained specific storage coefficient , *K* is the bulk modulus, and *B* is Skempton's coefficient. Substitution of (8) into (7) yields an equation that relates mean stress and pore pressure

$$\frac{\alpha}{KB}\left[\frac{\partial P}{\partial t} + B\frac{\partial \sigma_{kk}}{\partial t}\right] - \nabla \cdot (\frac{k}{\mu}\nabla P) = Q \qquad . \tag{9}$$

If displacement is chosen as the mechanical variable instead of stress, equation (9) can be re-written as

$$\frac{\partial}{\partial t}(S_e P + \alpha \nabla \cdot \boldsymbol{u}) - \nabla \cdot (\frac{k}{\mu}\nabla P) = Q \tag{10}$$

Equations (4) and (10) couple the standard theory of elasticity by the addition of the pore pressure field and can be solved by finite element or boundary element methods [*Smith & Griffiths*, 1988; *Masterlark & Wang*, 2000]. The coefficient S_e is related to the compressibility of the fluid and the porosity of the medium [*Showalter, 2000*]. In the case that $S_e > 0$ equations (4) and (10) are a parabolic system, whereas in the case that $S_e = 0$ the system is formally elliptic. The model couples the mechanical deformation and the fluid continuity equations for a variety of poroelastic problems.

Results.

To date, we have achieved the following milestones towards our proposed model development. This work reflects contributions from Dr. Ammon Meir (an expert in numerical analysis) and a graduate student, Ms. Chadia Affane, in Auburn's Department of Mathematics.

1. The deformation model 3-D DEF has been re-coded using MATLAB. The advantage of this re-coding is to facilitate "coupling" to the fluid pressure model in a common and widely utilized language. Our intention is that the completed code will be available and used by others doing similar studies.

2. A 2-D version of the fluid pressure model has been re-coded using MATLAB. Also completed is a MATLAB program to solve the continuity equation (equation 5) in 2-D for hydraulic head.

3. Equation (4) is solved for displacements and their derivatives using a 3-D finite element method in MATLAB. A body force (gravity) is assumed and pressure is initialized using 3-D DEF; that is, the volumetric strain derived from 3D-DEF is converted to stress and then the initial pressure is found by applying the Skempton condition with hydrostatic pressure.

Our next step in the process will be to use the displacement derivatives in the diffusion equation to solve for pore pressure. The resulting pressure will then be entered into the first program and the process iteratively repeated until convergence. Once the programs are complete and tested for stability, we will begin the field application to the NMSZ, as described in our original proposal. We will also make available the new MATLAB codes via the PIs websites.

Non-Technical summary.

This study is aimed at investigating the interrelationships of excess pore fluid pressures, seismicity, fault stability, and seismically induced liquefaction in the Mississippi Embayment. To achieve this goal, a new strain-fluid flow model will be developed and then applied to data observations from the New Madrid seismic zone. The newly developed model will consist of the integration of a 3-D crustal deformation program with a program that predicts fluid flow and pressure on a regional scale. The research will shed light on how the propagation of overpressures might affect deep fault stability and potential for near-surface earthquake-induced hazards.